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THEORETICAL AND EXPERIMENTAL STUDIES OF SPACE-RELATED
PLASMA WAVE PROPAGATION AND RESONANCE PHENOMENA

(SU-IPR-630) THEORETICAL AND EXPERIMENTAL
STUDIES OF SPACE-RELATED PLASMA WAVE
PROPAGATION AND RESONANCE PHENOMENA
Semiannual Report, 1 Jul. ~ 31 Dec. 1974
(Stanford Univ.) 16 p HC \$3.25

N75-26859

Unclas
26600

CSCL 201 G3/75

Semiannual Report No. 16
(1 July - 31 December 1974)

NASA Research Grant NGL 05-020-176

Principal Investigator:

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SU-IPR Report No. 630

March 1975



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NASA Research Grant NGL 05-020-176

for the period

1 July - 31 December 1974

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FOREWORD

The subject of NASA Research Grant NGL 05-010-176 is the theoretical and experimental study of space-related plasma wave propagation and resonance phenomena. Research supported by the grant has been proceeding under the direction of Prof. F. W. Crawford since its inception on 1 December 1966. This is the sixteenth semiannual report, and covers the period from 1 July to 31 December 1974.

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I. INTRODUCTION

The research to be discussed in this semiannual report is concerned primarily with plasma wave and resonance phenomena related to the ionosphere. Much of our previous work under the grant has involved direct laboratory simulation of puzzling effects occurring in space plasmas. Such projects led to better understanding of "Alouette" resonances, the resonance probe, some aspects of whistler propagation and triggered VLF emissions, and contributed to the development of a variety of new plasma diagnostic techniques. Particularly during the last decade or so, knowledge of plasma wave and resonance phenomena, in both the linear and nonlinear régimes, has advanced rapidly as a result of considerable study worldwide of space and laboratory plasmas, and many of the puzzling phenomena have been explained. It is consequently possible to plan experiments with greatly increased confidence in the theoretical predictions. The motivation and aims of our research program have progressed with these advances, and bring us naturally to the projects to be discussed in Sections II and III, particularly in relation to the NASA Space Shuttle Program.

The Space Shuttle Program offers exciting new possibilities for plasma physics experimentation. It is expected that, beginning in about 1980, the Shuttle Orbiter will carry as one of its regular payloads a "Spacelab", to be constructed by the European Space Research Organization. The Principal Investigator for this grant is a member of the Atmospheric, Magnetospheric, and Plasmas-in-Space (AMPS), Science Working Group, set up by NASA to study the appropriate instrumentation for Spacelab, and acts as chairman of the Plasma Wave Phenomena Section.

If the AMPS enterprise is to be successful, new space plasma experiments should be submitted to critical scrutiny for scientific merit and experimental feasibility. To be attractive, they should profit from the unique plasma environment and parameter ranges accessible to the Space Shuttle to perform basic plasma experiments not feasible in the laboratory, or to greatly improve others by virtue of the large volumes of essentially fully-ionized, collisionless plasma available for study; they should provide refined diagnostics for plasma conditions local to

the vehicle, and they should develop new techniques for improving understanding of the ionosphere itself by strong perturbation and by nonlocal probing, e.g. with electron beams or waves. Our aims under this grant are to test and refine various ideas for space plasma experimentation using Spacelab. Over the last twelve months, three Ph.D theses have been completed with support from the grant. This has given us the opportunity to phase out a number of projects, and to initiate others of more direct relevance to the Shuttle. The current program is described in Section II. Brief comments on likely directions for the second half of the grant year are made in Section III. A bibliography of Reports, Conference Papers, and Publications resulting from the grant during the reporting period, 1 July - 31 December 1974, is given in Section IV.

II. CURRENT RESEARCH PROGRAM

A. Whistlers and Alfvén Waves

We have been studying various aspects of whistler propagation over a period of several years, beginning with laboratory measurements of whistler dispersion characteristics in a cold collisional plasma, continuing with numerical studies of small-signal whistler instabilities, for propagation both parallel^{18,19} and oblique²⁰ to the earth's magnetic field in nonthermal plasmas, and finally extending this work to the nonlinear phenomena associated with triggered VLF emissions,^{21,22} modulational instabilities,²³ and Alfvén wave excitation. We have also studied excitation of VLF waves by charged particle beams,^{5,10} and ULF waves by metallic electric and magnetic dipole antennas,²⁴ as part of our most recent work. During the reporting period, except for some minor revisions to a previously published paper,⁶ and to a manuscript submitted for publication in the J. Geophys. Res. during the last reporting period,²⁴ the emphasis has been on whistler excitation by electron and proton beams.^{5,10}

Beam Excitation of Whistlers: A new method of generating VLF signals has been proposed recently in which helical electron beams, fired from satellites, are to be used to radiate whistlers.²⁵ The satellites are assumed to be instantaneously on the $L = 4$ shell at an altitude of 500 km. Electron beams of about 1 A current and 10 keV energy are to be injected from 20 satellite-mounted guns forming a circular array of the order of 100 m diameter. The frequencies and amplitudes of the whistlers radiated will depend on the pulse frequency, and angle at which the beams are injected into the earth's magnetic field. It has been claimed that the total power radiated from such a set-up will be at least of the order of 10 W, and that the power flux will be of the order of 10^{-4} W/m². The former is comparable to that achievable by large ground-based VLF transmitters.

* References 1-15 are to be found in Section IV. The remainder are given in Section V.

We have been considering the proposal carefully, and trying to determine the feasibility of carrying it out with Spacelab. We noted in SAR 15¹⁴ that the proposer of the idea had neglected to consider the stability of the beam to longitudinal wave growth. According to rough calculations of the growth rate of longitudinal instabilities, due to beam-plasma interaction,²⁶ we believe that the beam cannot travel more than about 10 m before its helical structure and phase coherence are broken up by such instabilities. This would have the effect of reducing the power radiated to about four orders of magnitude below the 10 W value mentioned above. The power calculated by us was that radiated within a propagation-vector cone-angle of 70° , at fixed frequencies of 10 and 45 kHz.

During the reporting period, we have refined our work by calculating the power radiated for a wider range of frequencies, and from within propagation-vector cone-angles corresponding to a range of duct enhancements (due to plasma density inhomogeneity²⁷) between 1.02 and 1.25. These more refined results verify that the radiated power is expected to be of the order of several mW. In addition to beam-plasma interaction, we have considered the effects of diffusion, space-charge spreading, and collisions, on the power radiated. We have also considered the merits of using an ion beam in place of the electron beam, and found the former to be superior to the latter with regard to radiation efficiency, although at the cost of a somewhat increased accelerating potential. We have identified in our analysis the term which gives rise to wave-particle interaction. This has allowed us to show that the waves which undergo wave-particle interaction are well outside the range which can be ducted, and therefore to explain why the power calculated by us is so much smaller than that calculated by Dowden. The results obtained have been described in detail in a recent report which has been submitted for publication.¹⁰

ULF Antennas: We have extended our consideration of the excitation of Alfvén waves at ULF by means of ground-based electric and magnetic dipoles. Our earlier work²⁴ showed that a field of 1 mV was produced at a horizontal distance of 1 km from an electric dipole of strength 8×10^4 coul-m, whereas with a comparable magnetic dipole, of strength

$2 \times 10^{13} \text{ amp-m}^2$, only $3 \times 10^{-5} \gamma$ were produced. These results were based on the fields generated by waves in the earth-ionosphere waveguide. Our latest work shows that one must also consider the lateral (i.e. continuous eigenmode) wave for the magnetic dipole case, and that this wave gives rise to a field strength of about 1 mV. Thus, the magnetic dipole excites ULF waves at the earth's surface which are fully comparable to those generated by an electric dipole. These revised results have been incorporated into the manuscript based on Ref. 24, which has been submitted for publication. No further studies of this method of ULF excitation are envisaged.

B. Nonlinear Wave Propagation

The success of perturbation theory in predicting small-signal plasma wave dispersion characteristics, has opened the way to more sophisticated analyses of nonlinear wave-wave and wave-particle interactions founded on the same basic equations, i.e. Maxwell's equations and either a microscopic, a macroscopic, or a cold plasma description of the charged particle dynamics. Such analyses are frequently at the limits of tractability, and either computer simulations or improved analytic formalisms are required to relieve the difficulties. We have studied both approaches extensively under this grant, and have brought several significant projects to a conclusion during the reporting period:

Computer Simulation: Plasma simulation on the computer entrains many problems of its own, in particular those of expense if a large number of charged particles are to be followed, and unwanted fluctuations if the number of particles is small. To avoid them, we have applied a hybrid method originally proposed by Denavit,²⁸ for effectively collisionless plasmas, which provides a virtually noise-free plasma. This method enables us to perform simulations at signal amplitudes small enough to satisfy the assumptions made in the theory: noise can be reduced by six orders of magnitude at computational costs within about a factor of two of previous methods. As an example, we have studied linear Landau damping numerically at a ratio of wave energy/plasma thermal energy four orders lower than in any previous work known to us.

This work was followed by simulations of large-amplitude longitudinal wave propagation. The wave distorts the time-averaged electron velocity distribution into double-humped form, which is unstable to sideband growth near the phase velocity of the large amplitude wave. In practice, sidebands would grow from noise. In our simulations, a small-amplitude test wave was injected, and its growth rate was measured. We found that the time evolution of the distortion of the spatially averaged distribution function agrees with analytical results developed previously under this grant,³⁰ and that the distortion of the averaged distribution function is responsible for the behavior of the sideband wave.

In addition to the sideband growth, additional satellite frequencies are generated involving other sidebands and the second harmonic of the large-amplitude wave. A plausible four-wave interaction mechanism intended to explain this was examined as part of our work under this grant, but proved inadequate to account for the amplitude of the satellite.³¹ A new mechanism was then considered, involving modulation of the large amplitude wave.²⁹ This proved highly successful in predicting the satellite amplitude.

During the reporting period, a conference presentation has been given,³ and two manuscripts on the simulation work have been submitted for publication.^{11,12} The first of these deals with the hybrid simulation method, treating both linear and nonlinear Landau damping as examples. The second deals with sideband and satellite growth. Our development of simulation techniques is now considered to be completed. We expect to use them on such problems as the velocity spreading of beams due to beam-plasma interaction.

Lagrangian Formalism: Work has been carried out at Stanford under this grant, over the last four or five years, to develop and use appropriate Lagrangian densities for the microscopic, macroscopic, and cold plasma formulations. The work is described in detail in three Ph.D. theses,³²⁻³⁴ the most recent of which was completed in June 1974 and dealt mainly with the macroscopic formulation.³⁴ Although no new work on Lagrangians has been carried out during the reporting period, preparation of some of the thesis material for publication has been undertaken. In particular, a manuscript on the inverse problem of the calculus of

variations, i.e. derivation of an appropriate Lagrangian from a given set of equations, has been written. One paper, comparing experimental results on nonlinear three-wave interactions with theoretical predictions, derived using Lagrangian methods, has appeared during the reporting period,⁷ and a conference presentation has been made on the linear problem of resonances in an inhomogeneous plasma,⁴ i.e. Tonks-Dattner resonances.

C. Long Delayed Echoes

From 1967 to 1973, an ionospheric sounding program was carried out at Stanford to determine whether a curious phenomenon reported by van der Pol and Störmer in 1928 really occurs or not, and if so to determine its origin. The effect is simply that radio signals, e.g. Morse dashes can occasionally return from the ionosphere with tens of seconds delay, rather than the few ms delay expected. Sporadic observations by a large number of amateurs lend credence to the idea that the effect is genuine, but no systematic studies have been unequivocally successful in demonstrating its existence. Some suggestive echo data from the Stanford experiments have led to a theory of the phenomenon based on beam-plasma interaction due to precipitating fast particles interacting with the ionosphere so as to allow low group velocity propagation (hence long delay) without undue collisional attenuation.³⁵

Last year, NSF support for the LDE program came to an end, and was replaced by support from this NASA grant. The observational program has not been continued, but we have strong reasons for pursuing the theoretical work: first, our most recent numerical results show very encouraging agreement with the observed characteristics of LDE,^{2,8} and second, the Space Shuttle offers the possibility of studying the phenomenon from the topside of the ionosphere. On the topside, there is less radio noise to contend with, and frequency usage is not constrained by FCC allocation. Consequently, much more comprehensive measurements should be obtainable rapidly.

During the reporting period, a Ph.D. thesis has been completed by Sears reviewing the results obtained at Stanford and elsewhere.⁸ The thesis also contains some preliminary steps towards an analysis of the

phenomenon. It is postulated that ordinary mode energy from the transmitter couples linearly into a longitudinal plasma wave, propagating with low group velocity (~ 1 km/s) along the earth's magnetic field lines, close to the ordinary mode reflection height. If there are some high-energy (\sim keV) electrons precipitating along the field lines, they may, through the mechanism of beam-plasma interaction, offset the considerable collisional damping that a low group velocity wave would otherwise suffer over times of the order of 10 s. The plasma wave may then couple linearly, for example, at a local plasma inhomogeneity, to the ordinary mode, which can propagate downwards to the receiver.

The initial calculations by Sears for plausible assumed high energy electron fluxes have two defects. First, the maximum integrated group delay is about 1 s, i.e. an order of magnitude too low, and second, the growth that the signal wave-packet must experience over some parts of its path, to compensate for damping over others, would drive the interaction into nonlinear saturation. Thus, a modified mechanism capable of predicting weaker growth and longer delay must be sought. During the reporting period, we have considered two additional factors: ionospheric drift, and plasma wave propagation oblique to the earth's magnetic field.

It was hoped that the effect of drift might be to increase the group delay appreciably, and possible to allow coupling out of the ionosphere to occur at the reflection height of the extraordinary mode. It was found, however, that plasma drifts ≥ 1 km/s would be required, i.e. appreciably larger than those reported in the literature.³⁶⁻³⁸ Our studies of growth rates and group delay for oblique propagation have only begun recently. It is anticipated that they will be concluded during the coming reporting period.

D. Pulse Propagation

Although the propagation of continuous waves through essentially homogeneous plasmas has been studied for over forty years, it is only in the last decade or so that transient propagation has received much attention. Under this grant, we have already conducted some pulsed propagation studies of cyclotron harmonic waves,³⁹ and obtained sufficiently good agreement with the theoretical dispersion characteristics

for the group delay to be used as a non-perturbing plasma diagnostic technique. With the Space Shuttle, the opportunity is offered of carrying out such experiments under conditions where instrumentation problems are very much simpler to solve than in the laboratory. It is our intention to examine the range of possible experiments. To begin with cold plasma propagation, packets in the ordinary and extraordinary modes could be excited with effectively delta-function pulses (~ 10 ns), and exhibit the features predicted by Brillouin and Sommerfeld around WW I.⁴⁰ These still await detailed verification with respect to such phenomena as "forerunners". Warm plasma wave propagation in the Landau and cyclotron harmonic modes could also be studied.

So far, our effort has been devoted to analyzing the wave-packets produced by delta-function excitation of a cold magnetoplasma. This should give two branches of right-hand polarized propagation, and one left-hand polarized branch, for wavevectors parallel to the earth's magnetic field. The analytical results must be studied numerically to make their significance apparent. This has been done during the reporting period. The numerical results allow us to identify the right- and left-hand polarized branches of the dispersion relation. For these waves in a weak magnetic field ($\omega_c/\omega_p < 0.1$), an approximate analytic solution has been found.

The whistler branch of the right-hand polarized mode can be distinguished in the numerical solutions. To first order, the velocity of propagation for this branch corresponds to the classical group velocity, $v_g/c = (27/64)^{1/2}(\omega_c/\omega_p)$. The detailed structure of the forerunners to this wave is effectively a rapidly increasing sinusoidal wave that merges into the main wave-packet. An analytic expression for the arrival of the whistler wave-packet is currently being developed, using an asymptotic method,⁴¹⁻⁴³ and should provide more detailed information on the structure of the forerunners. Preliminary results indicate that, for typical ionospheric parameters at heights of about 450 km, this expression for the whistler branch will be accurate to within 1% when the transmitter and receiver are separated by a distance of a few hundred meters or more.

E. Ionospheric Heating and Backscatter

Over the last few years ionospheric heating experiments have been carried out with the ESSA high-power (≈ 1 MW) sounder, near Boulder, and at Arecibo (Ref. 1 gives a brief review of the literature). Under such conditions, i.e. when a high-intensity signal propagates through the ionosphere, three separate nonlinear mechanisms can operate to increase the "resistive" losses above those due simply to the collisional effects included in linear theory. The mechanisms are:⁴⁴⁻⁴⁸ (a) thermal instability, (b) oscillating two-stream instability, and (c) parametric instability. The coupled-mode formalism that we have used in our wave-wave analyses under this grant provides a suitable approach to the last two mechanisms. With its aid, both of them can be shown to depend on the nonlinear interaction between ordinary, Langmuir, and ion-acoustic waves.^{49,50}

Such instabilities can be, and have been, studied by the radar backscatter technique. This raises an important question: though the heating signal may be effectively monochromatic, Langmuir and ion acoustic waves will be excited over a band of frequencies; what will be the shape of the backscattered spectrum? Solution of this problem involves taking account of the nonlinear saturation mechanisms which limit the parametric growth. During the reporting period, we have removed some of the shortcomings of a highly simplified approach developed under this grant about two years ago,⁵¹ and have obtained satisfactory predictions of the locations and separations of the main lines in the backscatter spectrum under conditions appropriate to Arecibo. This analysis has been written up recently for publication,¹³ and is regarded as completed.

III. FUTURE RESEARCH PROGRAM

A. Whistlers

We wish to pursue the project on the excitation of VLF waves by charged particle beams described in Section II A. In particular, it would be desirable to calculate the total power radiated by the beam, rather than just that part which is ducted. This would provide important information for experiments where receivers are to be located in the vicinity of the Shuttle. This calculation is not possible within the cold plasma analysis that we have used up to the present, since the fields become infinite at a certain angle, giving rise to an infinite radiation resistance. This is the familiar problem in antenna theory of the "resonance cone", and always occurs for waves which have open wave-normal surfaces. The difficulty can be removed by introducing electron temperature into the model, thereby giving rise to convergent integrals. We shall extend our analysis of the problem, by using warm plasma theory, in order to solve this important problem.

So far, we have considered a circular array in which all of the guns are mounted on the circumference and fired sequentially. Dowden's model distributes the guns over the circular area, and all are pulsed simultaneously.²⁵ We shall extend our theory to cover this case. It is expected that the power radiated will then be increased by about one order of magnitude.

B. Nonlinear Wave Propagation

It is anticipated that two papers will be written during the next six months on the Lagrangian formalism for the macroscopic plasma description developed in the thesis by Peng.³⁴ The first will describe the derivation of the appropriate Lagrangian and Hamiltonian densities; the second will consider perturbation expansions of the Lagrangian to obtain linear wave propagation and nonlinear wave-wave coupling coefficients. No further work on the formalism itself is envisaged: it will simply be used as occasion demands in our analyses of plasma wave and resonance phenomena.

C. Long Delayed Echoes

Further work is required to test the beam-plasma mechanism outlined in Section II C, and described in detail in Ref. 8. In particular, computations of group delays and growth rates for propagation oblique to the earth's magnetic field lines are required. A major publication will then be prepared embodying these results and those contained in Ref. 8.

D. Pulse Propagation

When the pulse propagation phenomena have been thoroughly studied for propagation parallel to the earth's magnetic field, including effects of positive ions and collisions, the analysis will be extended successively to the limiting case of perpendicular propagation, and the general case of oblique propagation. It will be of particular interest to determine which features of the wave-packet can be observed as measures of the ionospheric parameters (density and magnetic field).

E. Ionospheric Heating and Backscatter

In Section II E, we noted that ionospheric heating experiments had been carried out using ground-based transmitters located near Boulder and at Arecibo, and had yielded evidence of the excitation of nonlinear wave interactions. The Space Shuttle would allow a more modest transmitter antenna system to be carried, but still capable of providing similar power fluxes in the ionosphere. Since radar backscatter represents a powerful technique for studying the nonlinear interactions likely to result, involving transverse ordinary and extraordinary waves with longitudinal electron plasma and ion acoustic waves, we shall spend some time during the next reporting period investigating the feasibility of carrying an adequate backscatter system on the Shuttle to make both coherent and incoherent backscatter measurements.

IV. REPORTS, CONFERENCE PAPERS, AND PUBLICATIONS RESULTING FROM
NASA GRANT NGL 05-020-176 (1 July - 31 December 1974)

1. Crawford, F. W., "Heating Experiments in the Ionosphere"
*Proc. APS/IEEE Second Topical Conference on RF Plasma
Heating, Lubbock, Texas, June 1974 (IEEE, New York, N. Y.,
1974), Paper E1, 9 pp. [Invited paper].
2. Crawford, F. W., and Sears, D. M., "Experimental Observations and
a Proposed Explanation of Very Long Delayed Echoes from
the Ionosphere"
*Second European Conference on Cosmic Plasma Physics,
Oxford, England, July 1974
*URSI-IEEE Meeting, Boulder, Colorado, October 1974
*URSI XVIIIth General Assembly, Lima, Peru, August 1975
(to be presented).
3. Matsuda, Y., and Crawford, F. W., "Some Computational Studies of
Nonlinear Plasma Waves"
*25th Annual Meeting of Plasma Physics Division of
American Physical Society, Albuquerque, New Mexico,
October 1974
Bull. Am. Phys. Soc. 19, 915 (October 1974) [Abstract only].
4. Peng, Y-K. M., and Crawford, F. W., "Variational Calculations for
Resonance Oscillations of Inhomogeneous Plasmas"
*16th Annual Meeting of Plasma Physics Division of
American Physical Society, Albuquerque, New Mexico,
October 1974
Bull. Am. Phys. Soc. 19, 970 (October 1974) [Abstract only].
5. Kuo, Y. Y., Harker, K. J., and Crawford, F. W., "Generation of
Whistler Waves by a Helical Electron Beam"
*16th Annual Meeting of Plasma Physics Division of
American Physical Society, Albuquerque, New Mexico,
October 1974
Bull. Am. Phys. Soc. 19, 978 (October 1974) [Abstract only].
6. Harker, K. J., Crawford, F. W. and Fraser-Smith, A. C., "Generation
of Alfvén Waves in the Magnetosphere by Parametric
Interaction between Whistlers"
J. Geophys. Res. 79, 1836 (May 1974)
See also 79, 4827 (November 1974) [Errata].

IPR = Stanford University Institute for Plasma Research Report.

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7. Peng, Y-K. M., "A Comparison between Theory and Experiments on Nonlinear Three-Wave Interactions in Plasmas"
Int. J. Electr. 37, 667-688 (November 1974).
8. Sears, D. M., "Long Delayed Radio Echoes"
I.P.R. 584 (November 1974) [Ph.D. thesis].
9. Crawford, F. W., "Plasma Wave and Resonance Phenomena"
*European Space Research Organization Symposium on the Atmosphere, Magnetosphere, and Plasmas-in-Space (AMPS), Frascati, Italy, November 1974 [Invited paper].
I.P.R. 603 (December 1974).
10. Kuo, Y. Y., Harker, K. J., and Crawford, F. W., "Radiation of Whistlers by Helical Electron and Proton Beams"
I.P.R. 606 (December 1974)
J. Geophys. Res. (submitted for publication).
11. Matsuda, Y., and Crawford, F. W., "Computational Study of Nonlinear Plasma Waves: I. Simulation Model and Monochromatic Wave Propagation"
I.P.R. 607 (December 1974)
Phys. Fluids (submitted for publication).
12. Matsuda, Y., and Crawford, F. W., "Computational Study of Nonlinear Plasma Waves: II. Sideband Instability and Satellite Growth"
I.P.R. 608 (December 1974)
Phys. Fluids (submitted for publication).
13. Kim, H., Crawford, F. W., and Harker, K. J., "Analysis of the Backscatter Spectrum in an Ionospheric Modification Experiment"
I.P.R. 609 (December 1974)
J. Geophys. Res. (submitted for publication).

Semiannual Reports

14. No. 15 (1 January - 30 June 1974)
I.P.R. 580 (July 1974).
15. No. 16 (1 July - 31 December 1974)
I.P.R. 630 (March 1975).

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